Holographic Data Storage

Tien-Hsin chao
Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena
California, 91109
Phone:+818-354-8614 FAX: +818-354-1545
E-mail: Tien-Hsin.Chao@jpl.nasa.gov

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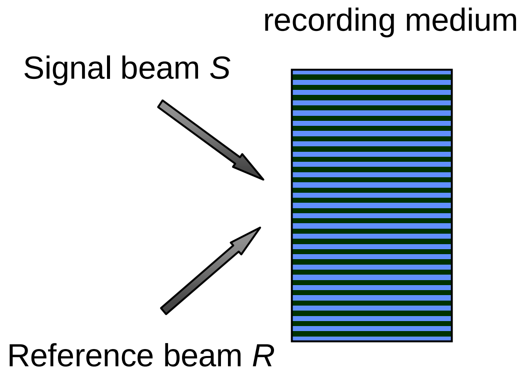
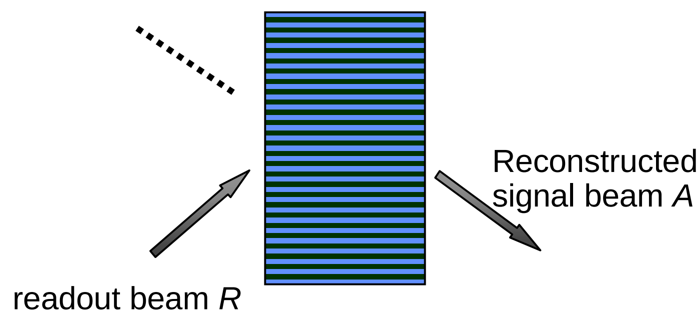
THIC Inc.
The Premier Advanced Recording Technology Forum

Holographic data storage

- Hologram recording
  - **fringe pattern**



- Hologram readout
  - **wavefront reconstruction**

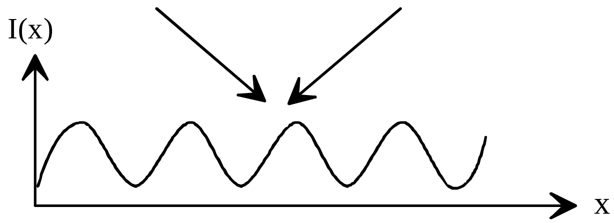


Photorefractive Materials as Recording Medium

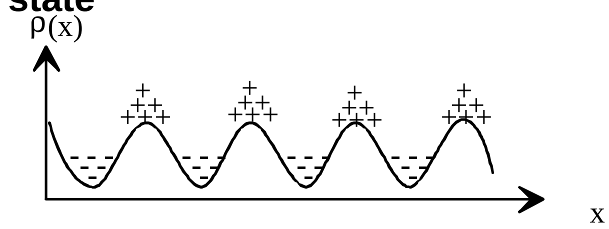
- **Refractive index change when exposed to an intensity pattern**

  (according to band-transport theory*:)

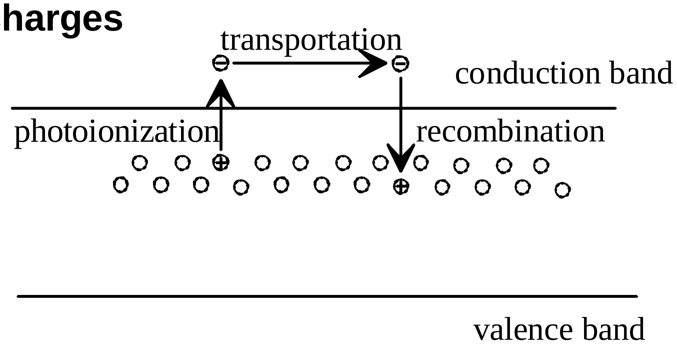
– **Interference pattern**

a) 

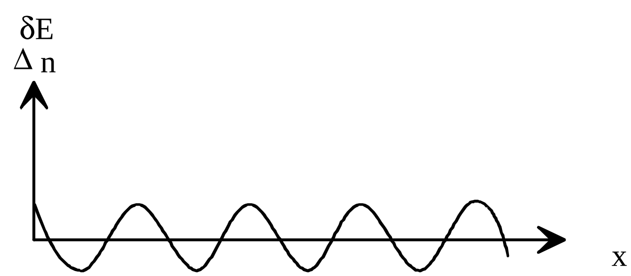
– **Space charge distribution at steady state**

c) 

– **Photogeneration and transportation of charges**

b) 

– **Refractive Index modulation via electro-optic effect ∝ space-charge field**

d) 

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* N. V. Kukhtarev *et al*, *Ferroelectrics* 22, 949 (1979).

Photorefractive Hologram Fixing

- **Photorefractive hologram decay/erasure:**
  - Light-induced erasure during repeat readout due to photoconductivity

    (high photoconductivity => fast photorefractive response, rapid erasure)
  - Dark decay during long-term storage due to dark conductivity

    typical dark decay: days ~ months, depends on materials

- **Fixing techniques:**
  - √ Thermal: heat recording medium, ~ 120°C

    for $LiNbO_3$, BSO, KNbO, BatiO
  - Electrical: apply external electric field, ~ kV/cm

    for SBN, BaTiO, KTaNbO
  - Periodic refresh:

  - √ Nonvolatile 2-photon recording

Thermal Fixing of Photorefractive Hologram

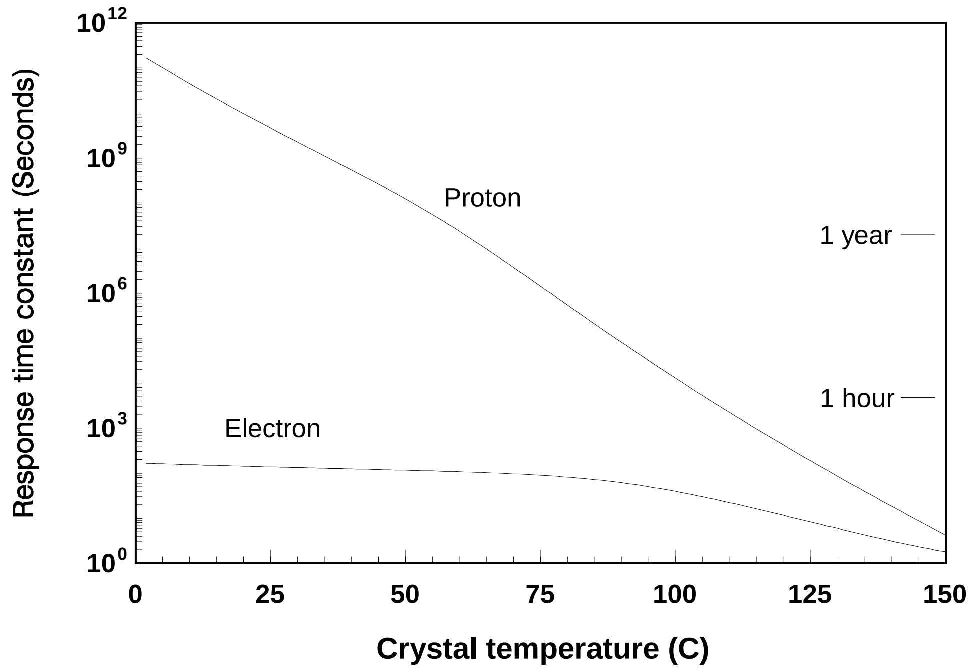
- **Heat the recording medium during or after the normal recording process, then cool it down to room temperature (and follow with an intense uniform illumination)**

  ==> electronic charge grating copied into ionic charge grating

  - **At room temperature, ions are "frozen".**
  - **At high temperature, ions become mobile and neutralize the electronic gratings (which remain relatively stable)**
  - **When cooled down, the ionic gratings are stabilized again while the electronic ones are partially erased by an intense illumination, leaving a fixed ionic space-charge field.**

- **Lifetime of fixed holograms: ~ years***

- **Typical time constants of the electron and the proton gratings in $LiNbO_3$ crystal**



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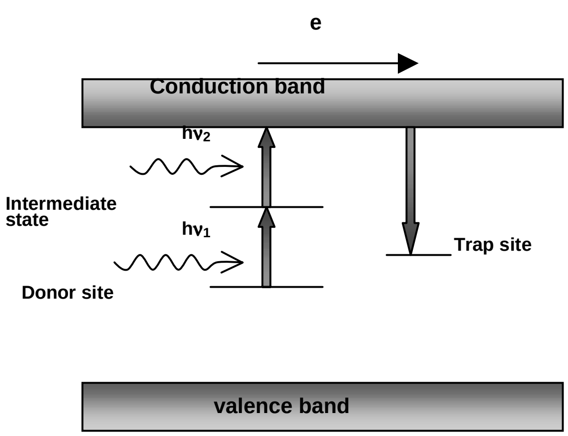
* **A. Yariv *et al*, *Opt. Lett* 20, p1336, 1995**

Nonvolatile Two-photon (or Gated) Recording

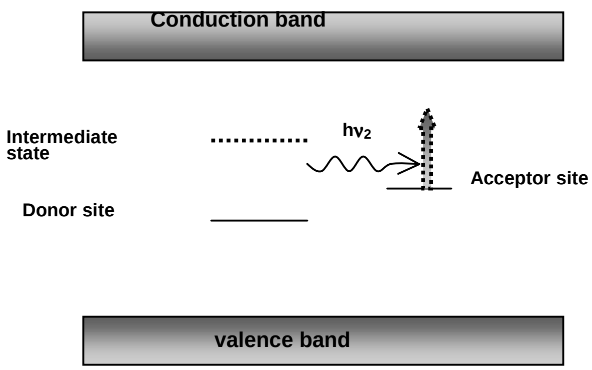
Recording

- First photon (e.g., uv, green) excites an electron to an intermediate state
- Second photon (e.g., red, near-IR) further promotes it to the conduction band
- The electron then migrates & gets trapped to record the interference pattern



Readout

- Readout by a single photon (e.g., red) ==> insufficient energy to promote electron to C.B., no photoexcitation
- No erasure of data
- To erase: use both photons



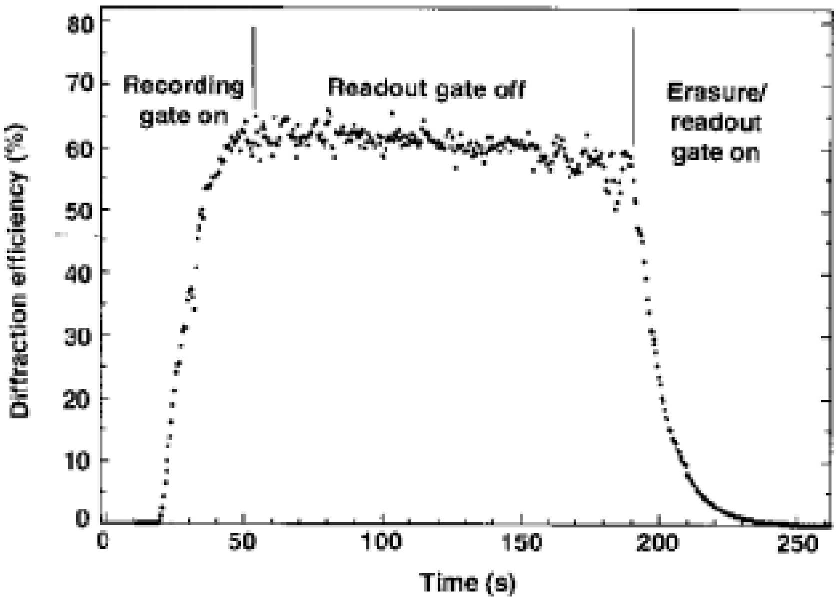
Nonvolatile Two-photon (or Gated) Recording

- **To achieve two-photon recording, materials must have:**
  - Deep traps that are partially filled with electrons, and
  - Shallow (intermediate) traps to trap photogenerated electrons with sufficiently long lifetime

- **Materials for two-photon recording:**
  - Pure (undoped) PR crystals, e.g. $LiNbO_3$
    - » Intrinsic defects (bipolarons induced by reduction) as intermediate states
    - » large dynamic range, low sensitivity
    - » Gating light: blue laser(476nm) , ~ 0.2 W/cm^2
    - » Writing light: near-IR (800nm) Ti:sappire, ~ 6 W/cm^2
  - Doped PR crystals, e.g., $Fe:Mn:LiNbO_3$
    - » Extrinsic dopants (Fe^{2+}, Mn^{2+}) provide intermediate states
    - » High sensitivity, small dynamic range
    - » Gating light: UV (365nm) mercury lamp, ~20 mW/cm^2
    - » Writing light: red HeNe laser, ~300 mW/cm^2

Nonvolatile Two-photon (or Gated) Recording

- **Comparison of gate-on and gate-off readout***
  - **Readout with gate off:**
    - no erasure
  - **Readout with gate on:**
    - erasure



*** undoped $LiNbO_3$,**
blue gating light, ~0.2W/cm²
IR writing light, ~6W/cm²

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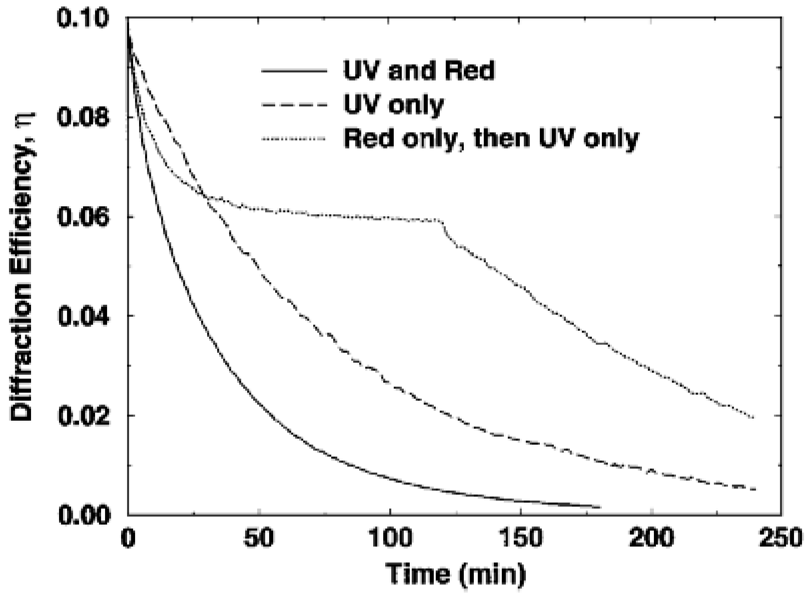
* **L. Hesselink *et al*, *Science* v.282, p1089, 1998**

Nonvolatile Two-photon (or Gated) Recording

- **Different readout/erasure methods in two-photon recording***

  - **Erasure w/ UV and red**
  - **Erasure w/ UV only:**
  - **Readout w/ red only (partial erasure), then UV only (erasure)**



*** Fe:Mn: $LiNbO_3$,**
UV gating light, ~20mW/cm^2
red writing light, ~0.3W/cm^2

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* D. Psaltis *et al*, *Opt. Lett*. 24, p652, 1999

Holographic Memory Light Budget

GOAL: Video-rate recording with storage capacity of 10,000 pages of 1,000x1,000 gray-scale images.

List of materials available for this application

	$LiNbO_3$ Fe	$LiNbO_3$ Fe, Mn	$LiNbO_3$ Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
thickness	√	√	√	*	*	√
shrinkage	no	no	no	yes (3%)	yes (3%)	yes (2%)
waveleng th	488nm	red+UV	red+blue	532nm	630-670nm	488nm
need fixing	yes	no	no	no	no	no
dynamic range	large	large	large**	modest	modest	modest
wiring speed	slow	very slow	slow**	very fast	fast	fast
rewritable	yes	yes	yes	no	no	no

* Thin materials only. Large-scale storage might be problematic with non-mechanical scanners.

** Projected.

For non-volatile storage of 10,000 holograms, the target diffraction efficiencies are,

$$\eta_h = \left(\frac{M/\#}{M} \right)^2$$

	$LiNbO_3$ Fe	$LiNbO_3$ Fe, Mn	$LiNbO_3$ Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
M/#	10*	10	30**	6	5	5
η_h	2.5×10^{-7}	10^{-6}	10^{-5}**	3.6×10^{-7}	2.5×10^{-7}	2.5×10^{-7}

* The M/# drops approximately by a factor of 2 after thermal fixing in $LiNbO_3$:Fe.
** Projected value.

1. Photon-limited readout: $N_e = \eta_{tr}\eta_q \frac{\eta_h \eta_{im} P_{in}}{h\nu} \frac{1}{r_{ON} N_p} t_{int}$

Variable	Definition	Value
Ne	number of signal electrons	~25,000*
η_{tr}	electron transfer efficiency	0.9**
η_q	quantum efficiency	0.9
η_h	hologram diffraction efficiency	**From above**
η_{im}	efficiency of readout optics	0.9
P_{in}	readout power	**?**
$h\nu$	power per electron	4.073×10^{-19} J
$r_{ON} N_p$	number of ON pixels	0.5×10^{6} ***
t_{int}	integration time	1 sec.

•For binary data, 100 photoelectrons at a pixel are needed for optimal hard thresholding, considering electronic, optical, and holographic noise.

** Worst-case transfer efficiency from CCD to external electronics.

*** Exact number for binary random-bit patterns.

* Projected value

Readout powers for 1-second integration time

	$LiNbO_3$ Fe	$LiNbO_3$ Fe, Mn	$LiNbO_3$ Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
P_{in} (mw)	28	7	0.07*	19	28	28

Recording speed

1. recording speed for 10,000 holograms (target diffraction efficiency is 10^{-7}).

	LiNbO3 Fe	LiNbO3 Fe, Mn	LiNbO3 Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
Writing energy mJ/cm^2	3	100*	1**	0.1	1	1
Writing intensity mw/cm^2	100	333*	33**	3.3	80	80

* For recording at He-Ne line. Data for blue recording is not available at the moment.

** Projected value.

Objectives and Major Products

- **UPN 632 Micro/Nano Sciencecraft Thrust**

- **Task Purpose: /Objectives:**
- Develop innovative nonvolatile, large-capacity, high-speed, read/rewrite compact holographic data storage system: Ultra High data/image storage capability (1TB);
- High-speed random access data transfer (1GB/s)

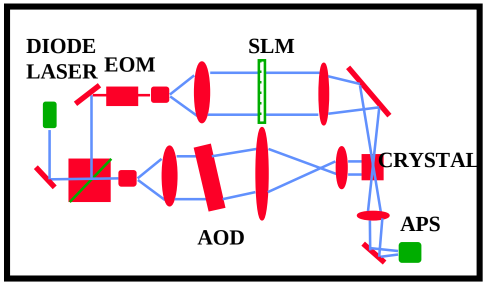
- **Major Products:**
- A compact holographic data storage with 10 GB non-volatile random access memory per cube with potential of reaching 1 TB memory board by stacking 10 x 10 cubes.

Technology Area Name

Objectives and Products

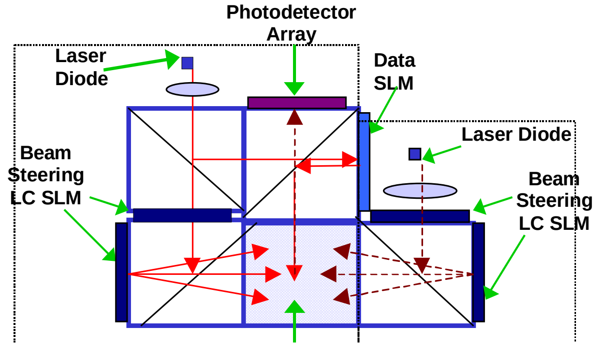
- Objectives :
  - **Develop innovative memory technologies to enable large-capacity, high-speed, read/rewrite of image and digital data in a space environment**
  - **Demonstrate key capabilities:**
    - Ultra High data/image storage capability (1TB)
    - High-speed random access data transfer (1GB/s)
    - Radiation-resistance
- Product Breakdown Structure:
  - **A compact holographic data storage with 10 GB non-volatile random access memory per cube**
  - **Up to 10 x 10 cubic memory can be stacked into an ordinary memory board size to achieve a storage capacity of 1TB**
  - **Read/rewrite, rad hard, high transfer rate**

Comparison of CHDS Technologies



Previous JPL CHDS using Acousto-optic scanner

Cubic Holographic memory using VECSEL array (Caltech approach)



Current JPL innovative approach using BS scanning devices

Pros

- AO device mature
- High-speed
- Medium density (x1 AO)

Cons

- Bulky (AO device requires lens set for beam forming)
- High-density storage requires 2 cascaded AO, very difficult for miniaturization

Pros

- Very compact using VECSEL array for multiplexing
- High-speed
- Medium density

Cons

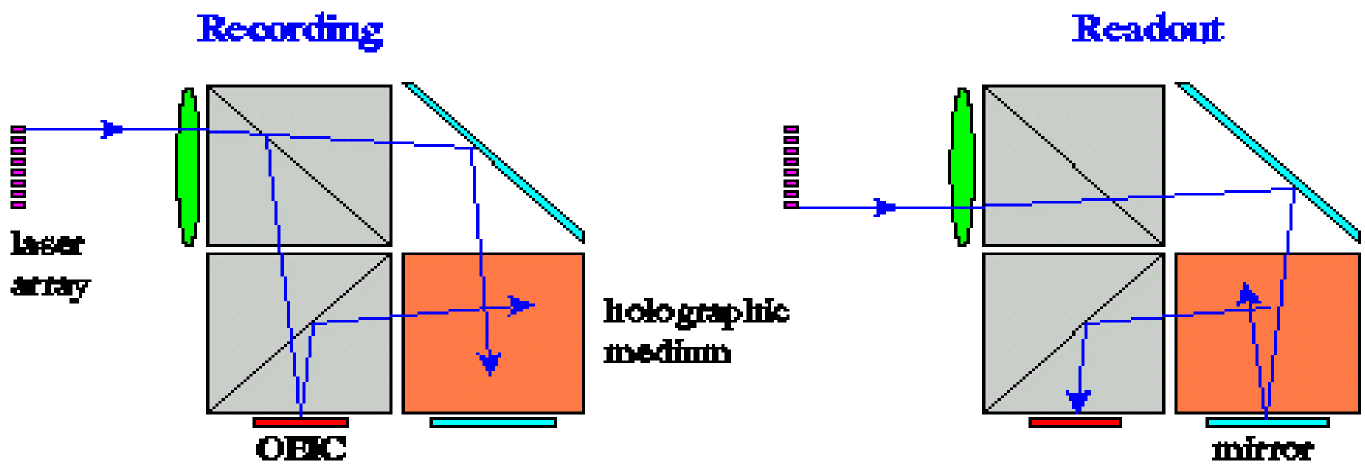
- High-density storage requires high-density VECSEL array
  - 10 x 10 array available to date
  - with only 4 mW power for each laser source (1/20 of needed power

Pros

- Very compact using BS device
- High-speed
- High density achievable with using 2 cascaded BS devices
- Use 2 single diode laser (commercially available)
- BS device is an emerging technology with a road map for performance optimization

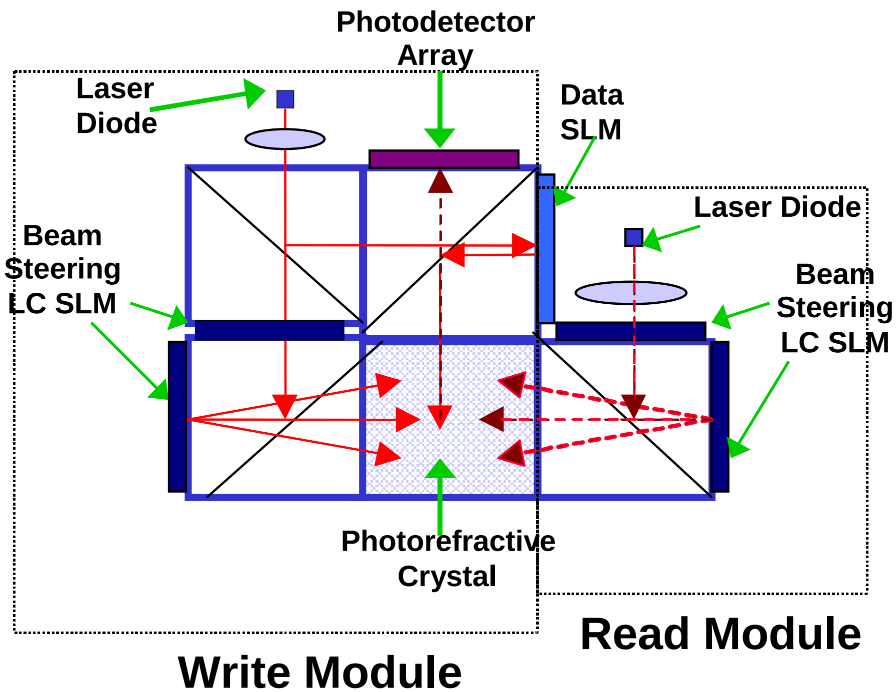
READ-WRITE HOLOGRAPHIC MEMORY CUBE

MEMORY OPERATION



- HIGH DENSITY COMPACT READ-ONLY MEMORY
  - 10,000 PAGES OF HOLOGRAM PER CUBIC INCH
  - 10 GBYTES STORAGE CAPACITY
  - UP TO 1000 PAGES PER SECOND READOUT RATE
- LOW VOLUME, MASS, POWER CONSUMPTION
- LENSLESS CONFIGURATION RESULTS IN DISTORTION-FREE DATA AND IMAGE RECALL
- VECSEL laser array not mature yet, 10 x 10 array with 4 mw each laser source is available now

System Schematic of an Advanced CHDS Architecture

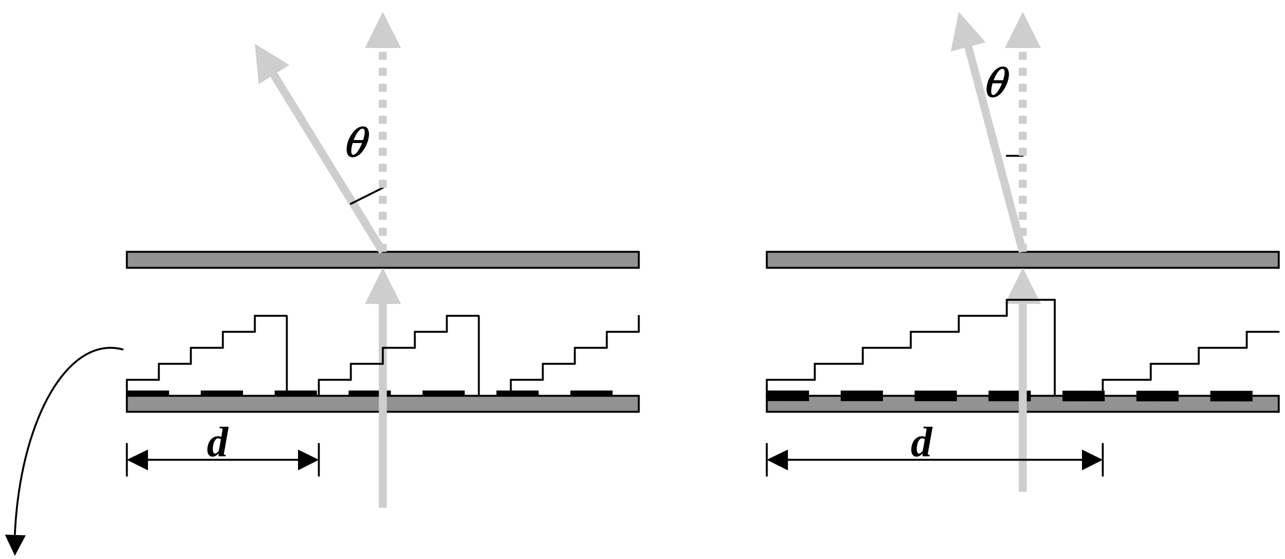


Unique Advantages

- **Very compact**
  - Cubic package with the size of a cigarette box
- **Massive data storage**
  - store up to 10^4 pages of hologram with 10 Gbytes capacity
- High-speed
  - current throughput 200 Mbytes/sec achieved with using a LC Beam Steering Device. Could be 10x faster if FLC is used
- **Device/components maturity**
  - Use two single diode lasers that are commercially available at low cost
  - Beam Steering Device is a emerging technology. JPL is actively engaged with BNS in developing the next generation high-speed version

Liquid crystal phased array beam steering device

- **Beam steering based on optical phase modulation**



Optical phase profile (quantized multiple-level phase grating) repeats every 0-to-2π ramp w/ a period *d* which determines the deflection angle θ

Liquid crystal phased array beam steering device

- **Diffraction efficiency:**

$$\eta = \left(\frac{\sin(\pi/n)}{\pi/n} \right)^2$$

***n*: number of steps in the phase profile**

***e.g.*, η ~ 81% for *n* =4, η ~95% for *n* =8**

- **Deflection angle:**

$$\theta = \sin^{-1}(\lambda/d)$$

for the first order diffracted beam

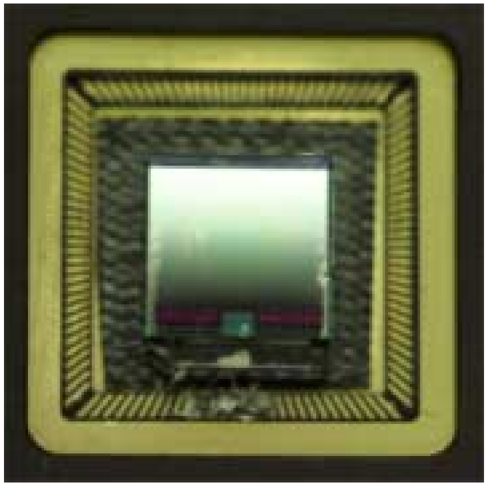
- **Number of resolvable angles:**

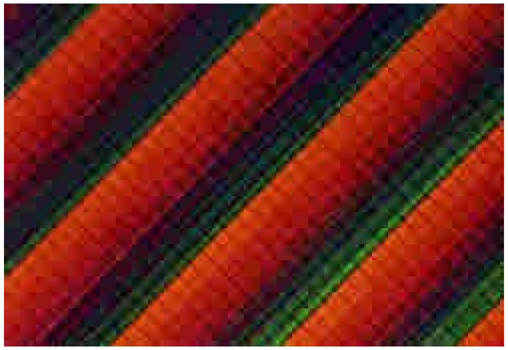
$$M = 2m/n + 1$$

***m*:pixel number in a subarray**
***n*: minimum phase steps used**

***e.g.*, *M* = 129 for *m*=512, *n* =8 with a 1x4096 beam steering device**

Photograph of a Liquid Crystal Beam Steering Device

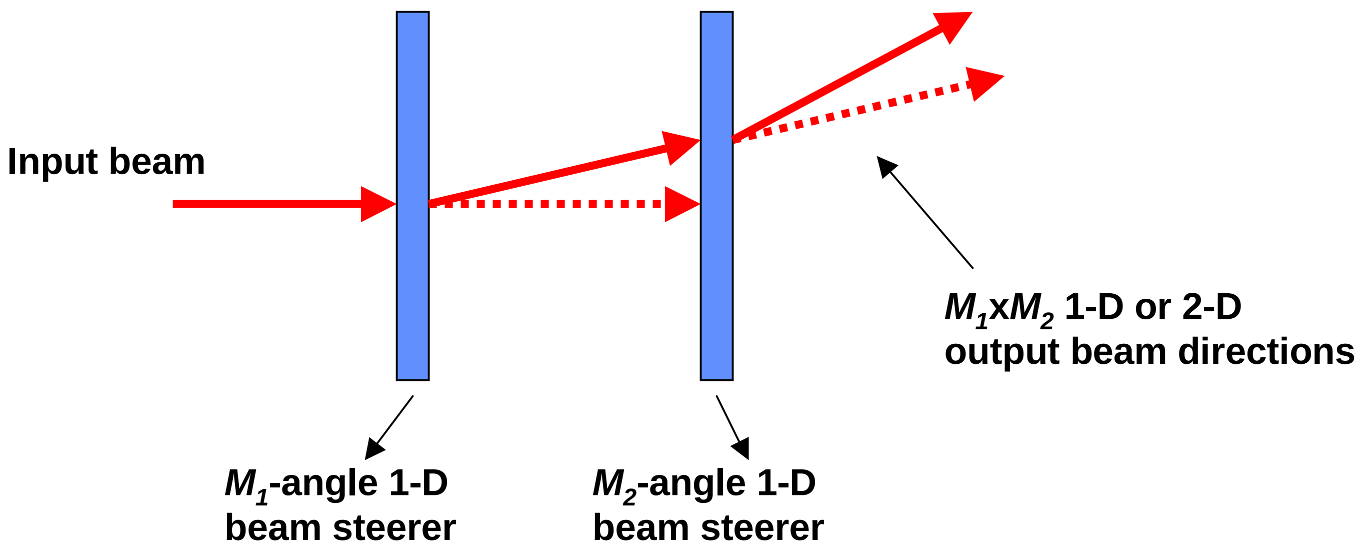




Surface phase-modulation profile of a beam steering device

Liquid crystal phased array beam steering device

- **Cascaded beam steering architecture:**



total resolvable angles of more than 10,000 can be easily achieved.

Liquid crystal phased array beam steering device

- **Benefits of using LC SLM beam steering devices:**
  - No mechanical moving parts
  - Randomly accessible beam steering
  - Low voltage / power consumption
  - Large aperture operation
  - No need for bulky frequency-compensation optics as in AO based devices

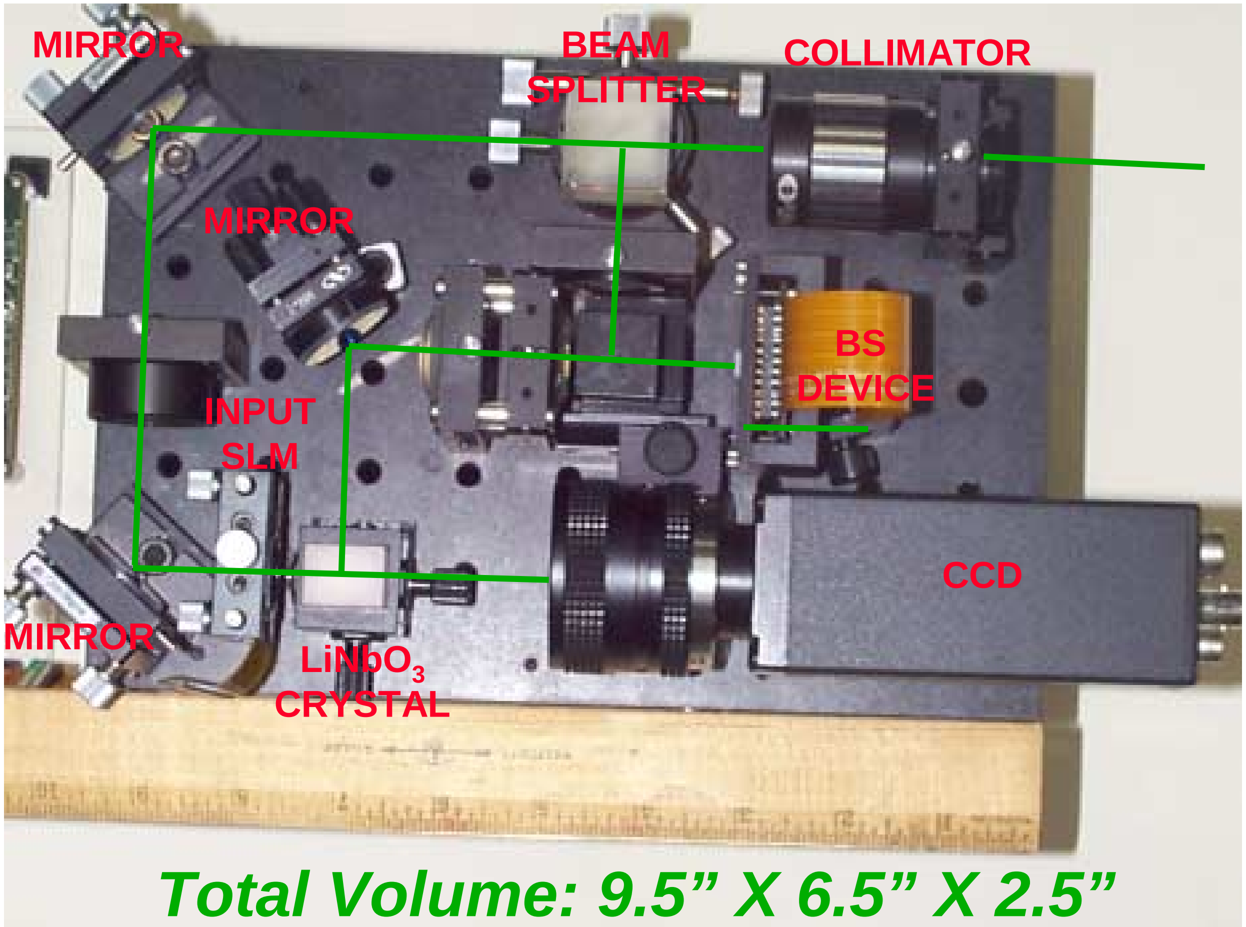
Performance Characteristics of LC Beam Steering Device

- **Number of pixels: 4096 Reflective**
- **VLSI backplane in ceramic PGA carrier**
- **Array size: 7.4 x 7.4 mm**
- **Pixel size: 1µm wide by 7.4mm high Pixel pitch: 1.8 µm**
- **Response time:**
  - **200 frames/sec with Nematic Twist Liquid Crystal**
  - **2000 frames/sec with Ferroelectric electric Crystal (under development)**

PICTURE OF A BOOK-SIZE CHDS
- Sponsored by NASA CETDP

An acousto-optics based Holographic Data Storage Breadboard developed in FY 1999

FY 2000 product: A book-sized CHDS breadboard



New 512 x 512 Grayscale Spatial Light Modulator

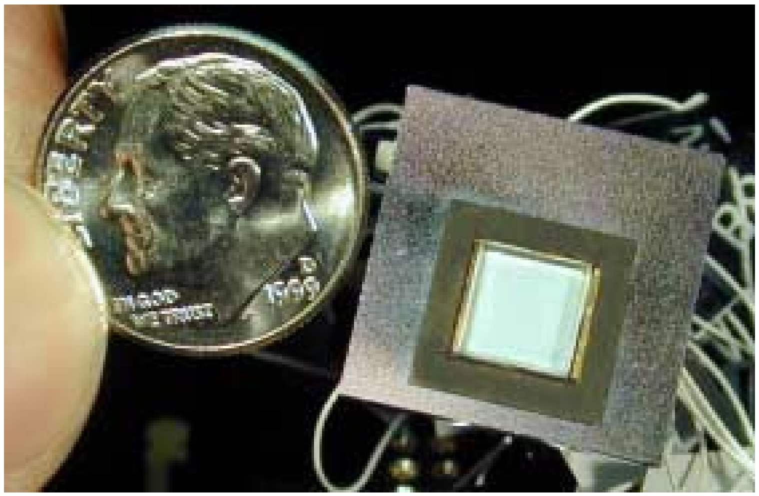
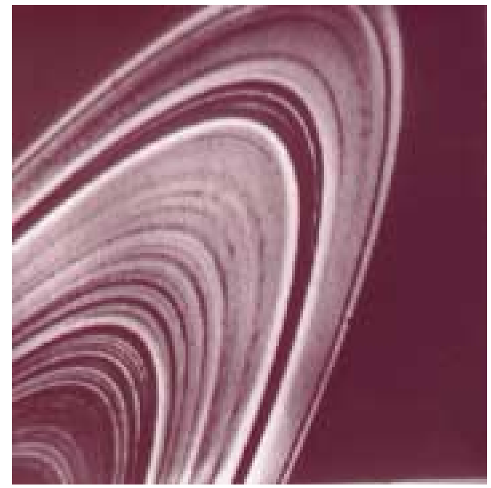


Photo of the new FLC SLM, much smaller than a dime

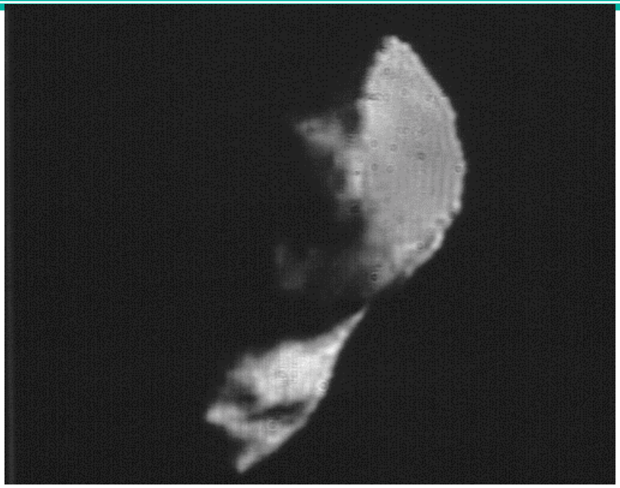


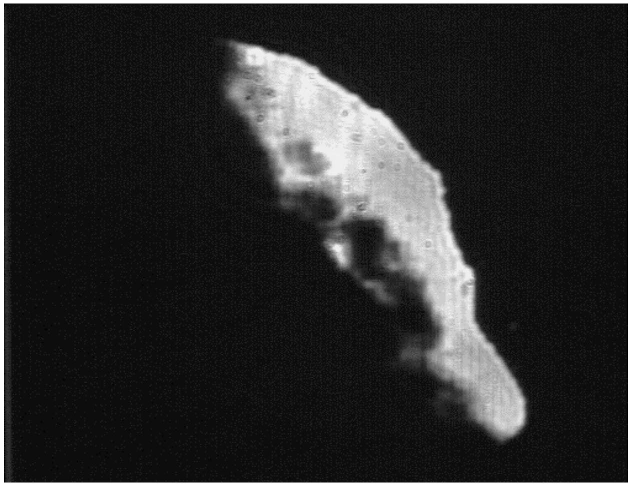
A high-quality grayscale image readout from the SLM

- New Grayscale SLM has been developed by Boulder Nonlinear System Inc. under a NASA/JPL SBIR Phase II program (T.H. Chao is the JPL contract monitor
  - **512 pixel x 512 pixel, 7- μm pixel pitch, 3.6 mm x 3.6 mm aperture size**
  - **High-speed at 1000 frames/sec**
  - **Enable high-density, high transfer rate data storage**
  - **Enable further system miniaturization**

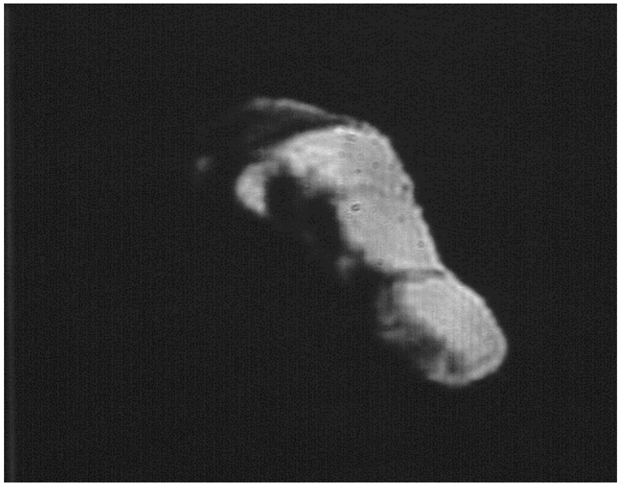
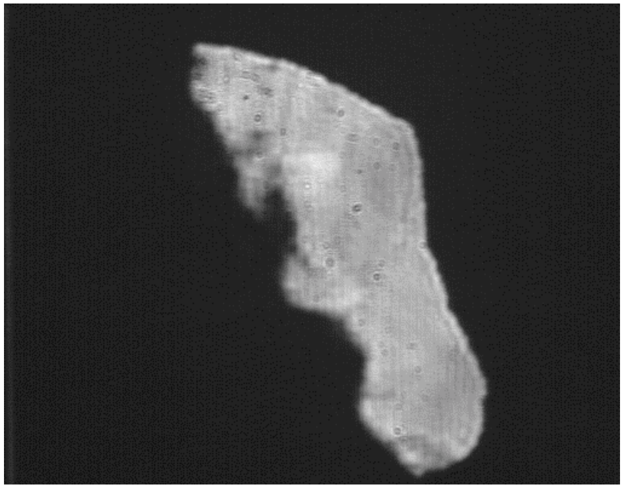
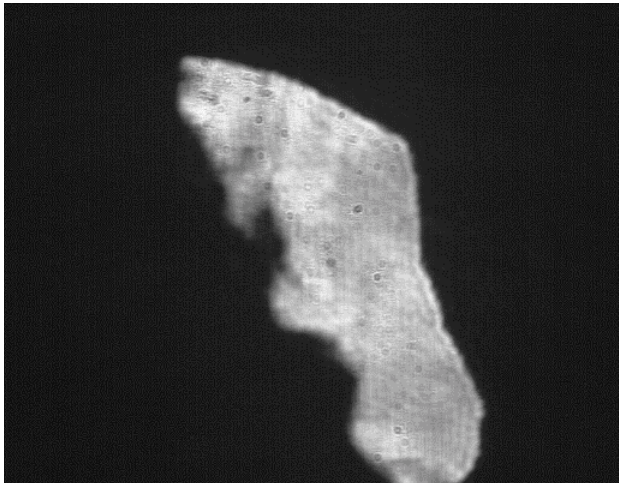
Holographically Retrieved Grayscale Images - Asteroid Toutatis

Input Images | Retrieved Holographic Images

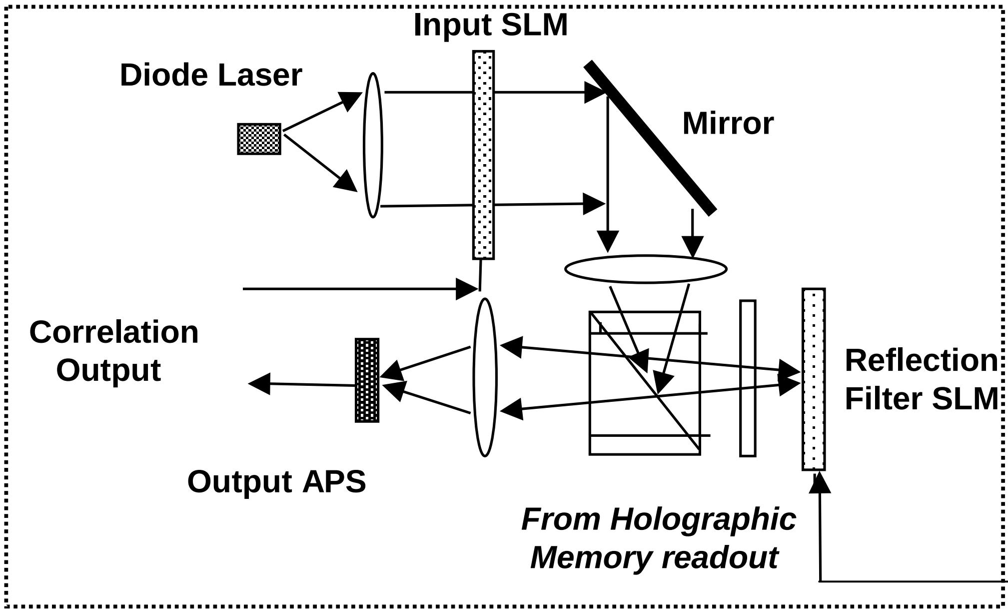




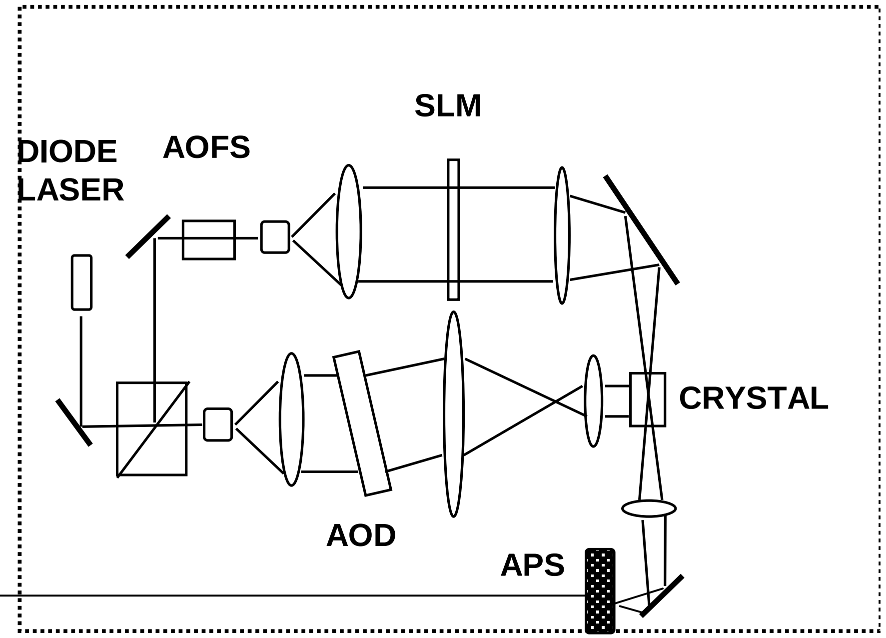
Holographically Retrieved Grayscale Images - Asteroid Toutatis

Input Images	Retrieved Holographic Images
	
	

System Schematic of an Optical Correlator using a Massive holographic memory correlation filter bank



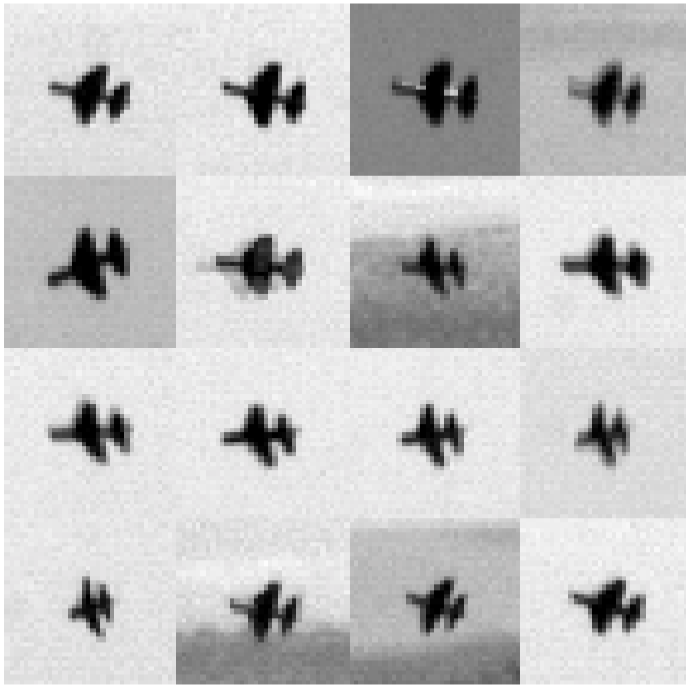
Grayscale Optical Correlator



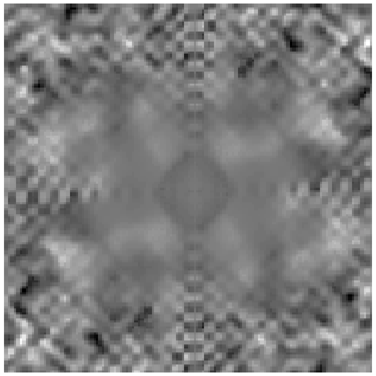
High-Density Holographic Memory

System architecture of an optical correlator using holographically stored and retrieved filter data for real-time optical pattern recognition. (a) A grayscale optical correlator and (b) an AO based holographic memory system

Example Training Image Set and Corresponding MACH Filter Image

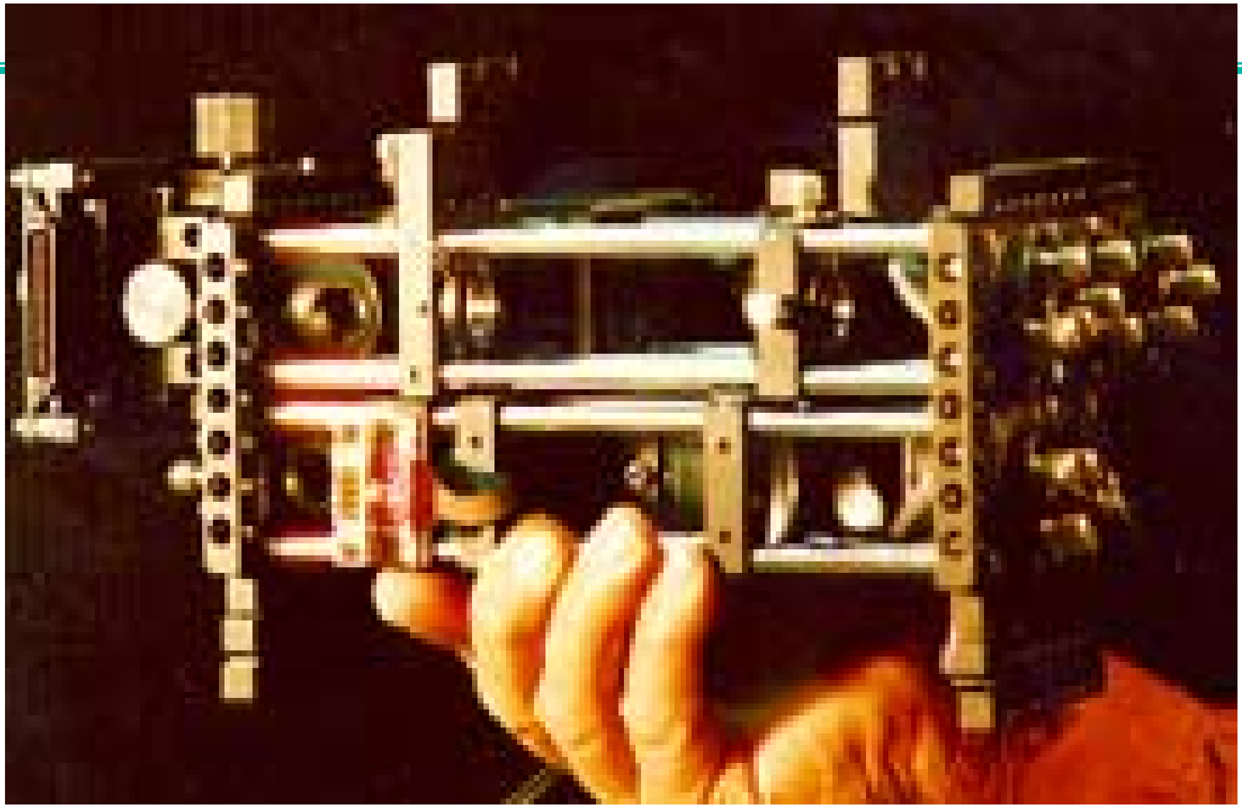


Training Image Set



MACH Filter Image

JPL Developed Grayscale Optical Correlator

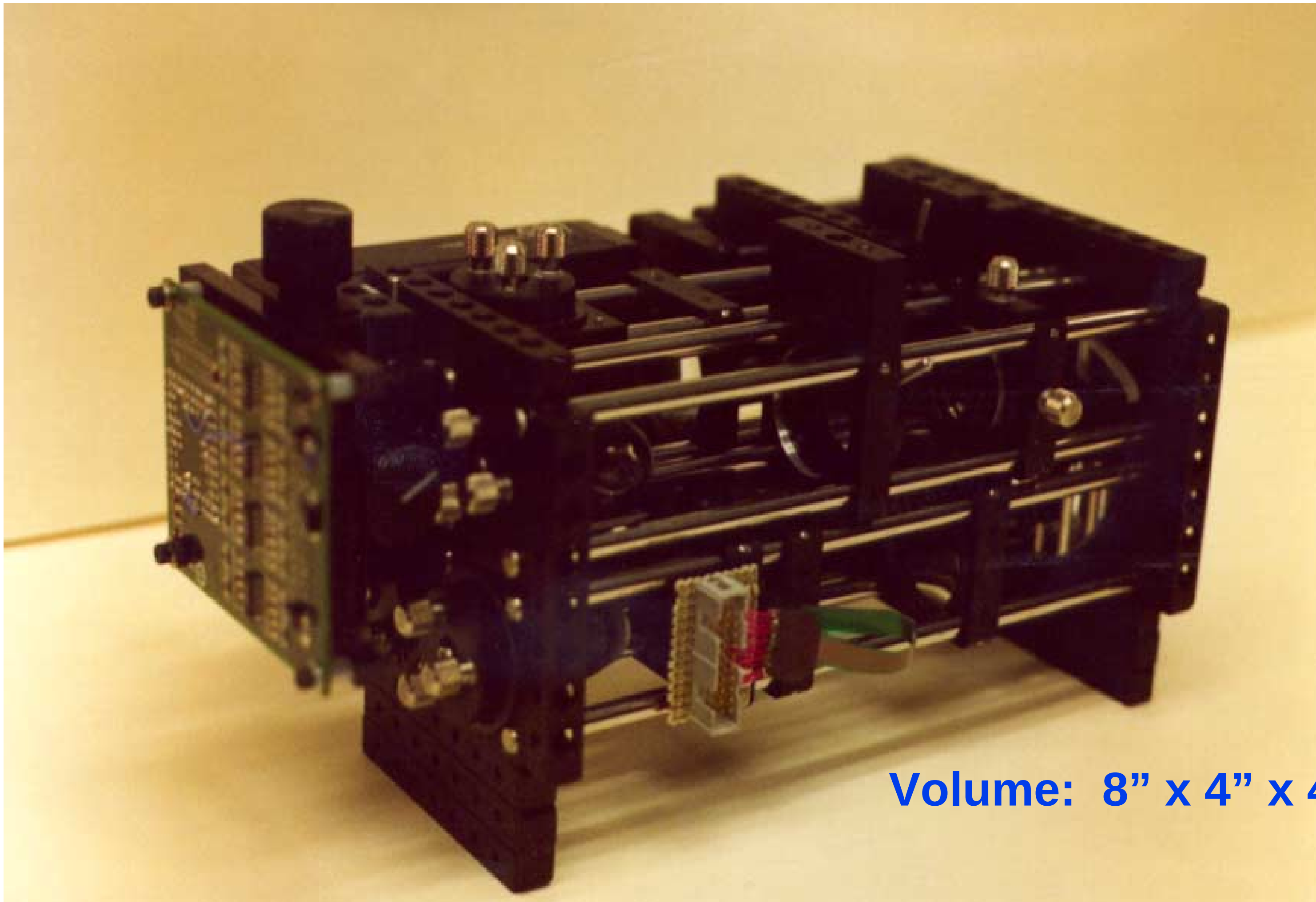


A camcorder-sized Grayscale Optical Correlator Developed at JPL

PRIMARY FEATURES

- **CAMCORDER SIZE (8” X 4” X 4”),**
- **ULTRAHIGH SPEED (1000 FRAMES/SEC), 30 TIMES FASTER THAN VIDEO RATE**
- **GRAYSCALE RESOLUTION (8 BIT INPUT, BIPOLAR 6 BIT FILTER)**
- **DIRECT COUPLED TO VIDEO SENSOR**
- **REAL-VALUED FILTER MODULATION ENABLES SMART FILTER ENCODING**

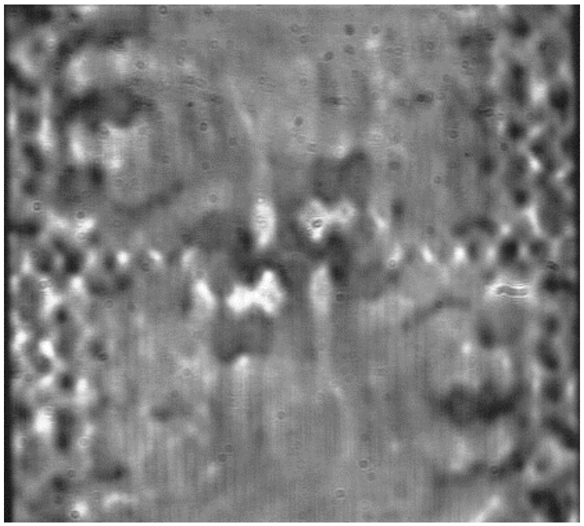
JPL's High-speed Compact Grayscale Optical Correlator

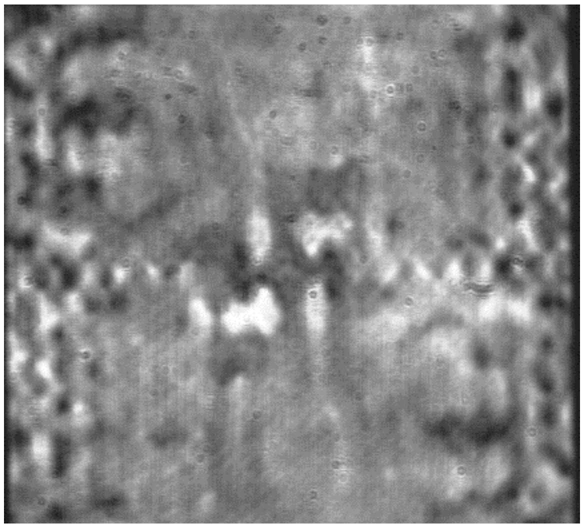


Volume: 8" x 4" x 4"

Experimental Result of MACH Filter Storage/Retrieval

- A MACH filter, capable of recognizing a class of airplane images, to be stored into the holographic memory
- The MACH filter image, retrieved from a holographic memory





CAMCORDER-SIZED GRAYSCALE OPTICAL PROCESSOR FOR AUTOMATIC TARGET RECOGNITION

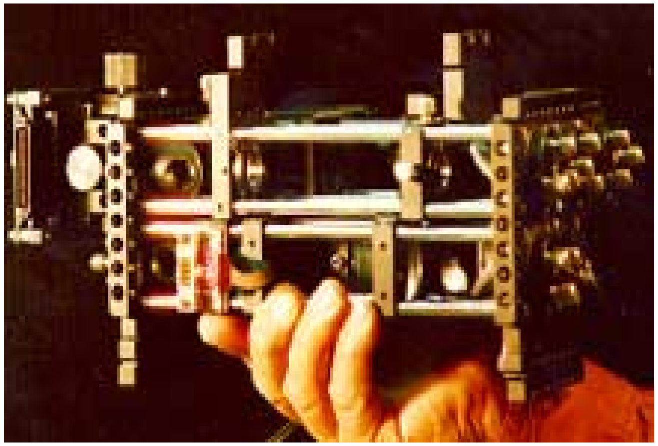
FOR THE FIRST TIME, JPL DEVELOPED A GRAYSCALE, COMPACT , AND ULTRAHIGH SPEED OPTICAL PROCESSOR AND DEMONSTRATED FOR AUTOMATIC TARGET RECOGNITION (ATR)

PRIMARY FEATURES

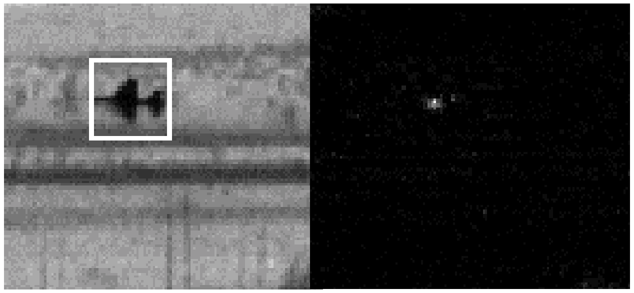
- REAL-TIME AUTOMATIC TARGET DETECTION AND RECOGNITION FOR BMDO
- CAMCORDER SIZE (8” X 4” X 4”),
- ULTRAHIGH SPEED (1000 FRAMES/SEC), 30 TIMES FASTER THAN VIDEO RATE
- UNIQUE GRAYSCALE RESOLUTION ENABLES HIGH DISCRIMINATION AND INVARIANCE IN A CLUTTERED/NOISY BACKGROUND

APPLICATIONS

- REAL-TIME ON-BOARD ATR FOR
  - CRUISE MISSILE DEFENSE
  - MISSILE SEEKER AIMPOINT SELECTION

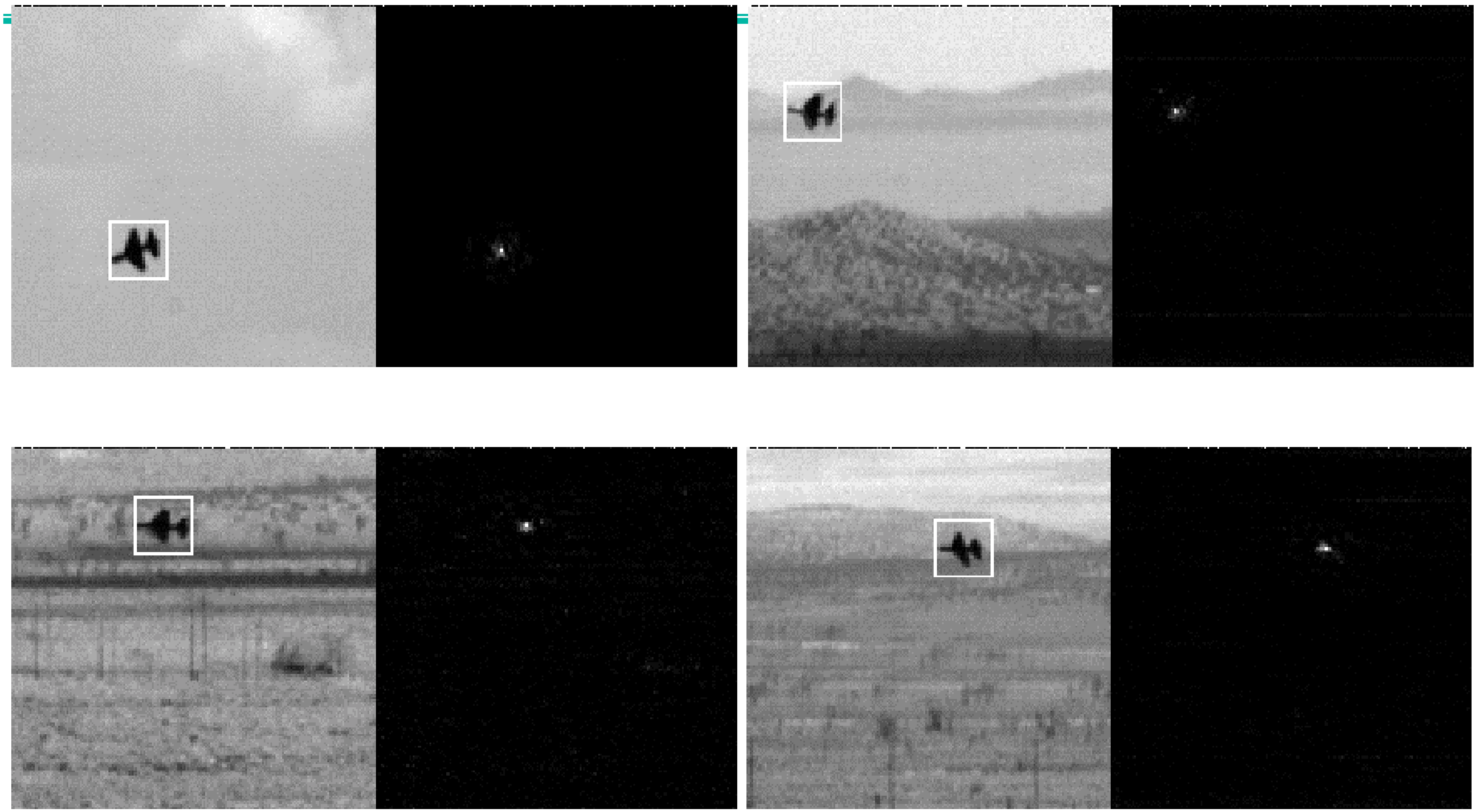


JPL developed camcorder-sized Grayscale Optical Correlator - Funded by BMDO / IS&T



Input Target **Correlator Peak**

1998 Real-time field tech demo for real-time target recognition and tracking of a Vigilante test vehicle (at Mojave, CA) using JPL’s optical correlator



- ***Real-time Recognition and Tracking of a Flight Test Vehicle With Different Scale, Orientation, and Background Clutter***